HIGH-RESOLUTION TRANSMISSION ELECTRON MICROSCOPY OF METEORITIC AND TERRESTRIAL NANO-DIAMONDS

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Introduction: Primitive meteorites contain within their bulk matrices a few parts per million of pristine interstellar grains that have survived the various mineral formation, accretion, and alteration processes that produced the meteorite parent bodies. These grains represent our only direct specimens of (surviving) physical material formed in past interstellar environments which we can subject to quantitative laboratory analysis. Interstellar grains were recognized from their isotopic compositions which are anomalous with respect to the solar mean and they were subsequently isolated and identified (graphite [1], silicon carbide [2,3], and diamond [4,5]). The most abundant of these carbon-rich components is diamond [6]. This abundance may not be representative of its distribution in the interstellar medium but most likely reflects its durability to pre-solar processing. The strong covalent tetrahedral bonds in the diamond structure make it highly resistant to alteration from: annealing, radiation damage, and chemical processing.

In this study, interstellar diamond crystallites isolated from acid dissolution residues of carbonaceous meteorites (Allende and Murchison) were systematically examined using high-resolution transmission electron microscopy (HREM). The distribution, density, and types of microstructural defects present in these nanocrystallites are heavily dependent on the details of the kinetics and energetics of the growth mechanism and are characteristic of the particular formation mechanism which produced them. Therefore, a detailed examination of the microstructures can be used to extrapolate information pertaining to the localized environments of diamond formation. To discriminate among the most likely formation mechanisms, microstructural features observed in the HREM images of the interstellar diamond crystallites are compared to those observed in terrestrially synthesized nano-sized diamonds formed from low pressure [4] chemical vapor deposition (CVD) and from high pressure shock waves [7] produced in controlled detonations [8].

Discussion: A JEOL JEM-4000EX high-resolution transmission electron microscope, operating at 400 KeV with a point-to-point resolution of 0.17nm equipped with a CCD video camera was used for the HREM imaging. The microstructures of the meteoritic diamonds exhibit extensive twinning. The most common and lowest energy twin boundary is a first-order Σ=3 (coincidence lattice site notation [9]) boundary with a {111} coherent twin plane. In a lower abundance, multiple Σ=3 twin boundaries are also observed. The most striking of these microstructures has a star configuration similar to those commonly observed in CVD diamond films [10] (Fig. 1a & 1b). Because of a 7.36° misalignment of the lattices, it is impossible to have five coherent Σ=3 twin boundaries sharing a common core. However a nano-sized structure can readily accommodate this misalignment by elastic strain at the twin interfaces (Fig 1a). Single and multiple Σ=3 twin boundaries are also observed in the terrestrially shocked diamonds, however no twin quintuplets (stars) have been observed. The shocked diamonds also differ in that they exhibit a large density of dislocations that are not observed in the meteoritic diamonds.

Type III hexagonal diamond (lonsdaleite) has been identified in the meteoritic acid dissolution residues (Fig. 1d). Lonsdaleite has been previously associated with meteorites; however, its formation there is attributed to terrestrial impact or recent meteoritic collisions in the early solar system [11, 12]. Since there is no evidence in Allende or Murchison for the shock levels necessary to produce lonsdaleite, the observed lonsdaleite is plausibly identified as an interstellar grain constituent. Although lonsdaleite is associated with shock processes, it is feasible that under certain CVD conditions that the kinetics would be favorable for the formation of the hexagonal polymorph [13]; this is further suggested from its observed nano-scale epitaxial growth on cubic diamond (Fig. 1c). This should impose additional constraints on the diamond forming interstellar environment. As expected, lonsdaleite is observed in diamonds synthesized in high pressure shock waves. It occurs as single crystals and in narrow (several unit cells wide) shock lamellae within cubic diamond nanocrystallites. These preliminary results indicate that the microstructures of the meteoritic diamonds are more consistent to those observed in CVD diamonds than those of shocked diamonds. This does not rule out shock processes as a diamond formation mechanism. However, it does suggest that the majority of observed meteoritic diamonds were formed from CVD-type low pressure processes.

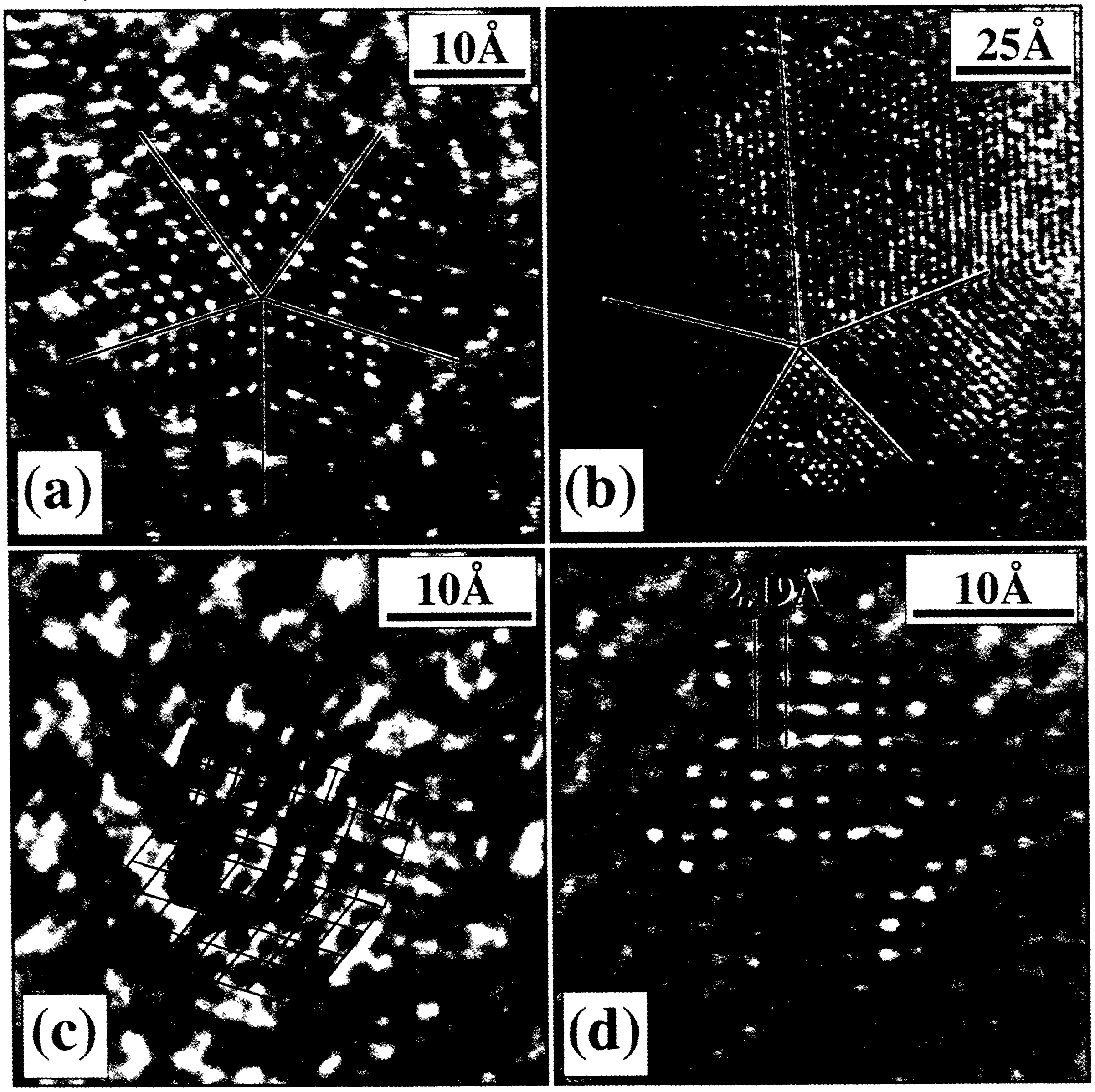

Figure 1: HREM atomic resolution lattice images of meteoritic diamonds. (a) A twin quintuplet exhibiting pseudo five-fold symmetry in Allende DM. (b) A larger pentagonal multiple-twin microstructure in Murchison X. These nano-stars are presumably formed in the circumstellar shells of distant stars. (c) An epitaxial intergrowth of cubic and hexagonal diamond (lonsdaleite) in Allende DM. (d) Single crystal of lonsdaleite in Murchison X.

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